315mJ, 2-µm Double-Pulsed Coherent Differential Absorption Lidar Transmitter for Atmospheric CO_2 Sensing

Mulugeta Petros[1]
Jirong Yu[2], Bo Trieu[2], Yingxin Bai[3], Grady Koch[2], Songsheng Chen[3], Paul Petzar[4], Upendra N. Singh[2], Michael J. Kavaya[2], Jeffrey Beyon[2]

[1]Science and Technology Corporation, 10 Basil Sawyer Drive, Hampton, VA 23666 USA
757-864-8583, m.petros@larc.nasa.gov
[2]NASA Langley Research Center, MS 474, Hampton, VA 23681 USA
[3]SSAI, One Enterprise Parkway, Suite 300, Hampton, VA 23666 USA
[4]NIA, 100 Exploration Way, Hampton, VA 23666 USA

ABSTRACT

The design of a double pulsed, injection seeded, 2-µm compact coherent Differential absorption Lidar (DIAL) transmitter for CO_2 sensing is presented. This system is hardened for ground and airborne applications. The design architecture includes three continuous wave lasers which provide controlled 'on and 'off' line seeding, injection seeded power oscillator and a single amplifier operating in double pass configuration. As the derivative a coherent Doppler wind lidar, this instrument has the added benefit of providing wind information. The active laser material used for this application is a Ho: Tm:YLF crystal operates at the eye-safe wavelength. The 3-meter long folded ring resonator produces energy of 130-mJ (90/40) with a temporal pulse length around 220 ns and 530ns pulses for 'on' and 'off' lines respectively. The separation between the two pulses is on the order of 200µs. The line width is in the order of 2.5MHz and the beam quality has an M^2 of 1.1 times diffraction limited beam. A final output energy for a pair of both 'on' and 'off' pulses as high as 315 mJ (190/125) at a repetition rate of 10 Hz is achieved. The operating temperature is set around 20°C for the pump diode lasers and 10°C for the rod. Since the laser design has to meet high-energy as well as high beam quality requirements, close attention is paid to the laser head design to avoid thermal distortion in the rod. A side-pumped configuration is used and heat is removed uniformly by passing coolant through a tube slightly larger than the rod to reduce thermal gradient. This paper also discusses the advantage of using a long upper laser level life time laser crystal for DIAL application. In addition issues related to injection seeding with two different frequencies to achieve a transform limited line width will be presented.

1. INTRODUCTION

There is a great urgency to comprehend the process of CO_2 exchange in the context of global climate change. Knowledge of the spatial and temporal distribution in addition to the natural and man-made sources/sinks in a global scale is crucial to predict and possibly manage the carbon cycle process. Most of the CO_2 measuring instruments, which contributed to the present knowledge base, are passive instruments that measure flux near the ground. In response to the challenges, laser based active instruments are being developed. These instruments rely on the measurements of the differential absorption between different wavelengths. Researchers at NASA Langley Research Center have been looking at this problem and have used an instrument initially designed as a wind coherent Doppler lidar, to measure CO_2 concentration [1-4]. The attractive feature of this instrument is that the laser material has a long upper laser lifetime, and as a result can produce two or more consecutive pulses within a few hundred microsecond spacing with a single pump pulse. This is an important consideration in terms of overall system design.

The operating wavelength around 2-µm has a favorable weighting function near ground surface [5]. The R (30) CO_2 line at 2050.967 nm (4875.75 cm-1) is selected for its temperature insensitivity, absorption strength and absence of absorption from other species [5, 7].

2. TRANSMITTER DESIGN

The transmitter architecture consists of a master oscillator and power amplifier system. With the amplifier operating in a double pass mode. The locking, offsetting and the switching of the seed laser which is described in detail by Koch et al [8], is housed separately. This portion consists of three seed lasers. One locked to the CO_2 absorption center though a pressure-controlled gas cell, in which the pressure is lowered 4 torr to narrow the absorption width for better discrimination. The second laser is offset from the center line by 4GHz from the absorption center. This is used as the 'on' line

wavelength and routed to a switch along with a third laser tuned to 'off' line wavelength. The fiber based switch alternates the two wavelengths. The line width measurement of the seed laser is done by beating two similar lasers, the result showed a line width below 13-KHz.

The lidar transmitter is housed in a sealed enclosure purged with dry air. The overall dimension of the system enclosure is 67cm x 16.5cm x 26cm. It houses the optical bench which is populated on both sides. The oscillator and the amplifier are mounted on one side, and local oscillator associated optics, and the receiver detectors on the other. The continuous wave laser is fed in to the transmitter enclosure with a fiber feed through.

The bench is temperature controlled to avoid any thermal induced misalignment. All the optical mounts are designed to be adjustable, lockable and hardened to withstand vibrations that can occur in ground or airborne operation. The most important system requirements are shown in Table 1.

Table 1. Transmitter specifications

Laser material	Ho:Tm:YLF
Output energy (mJ)	190/125 on/off
Wavelength(μm) both pulses injection seeded	2.050125/ 2.050967
Repetition rate (Hz)	10/10 on/off
Pulse separation (μs)	~250
Pulse length(ns)	200/520
Line width(MHz)	<2.5
LO frequency offset(MHz)	105
Telescope aperture (cm)	15

Two features make this work unique from similar work presented before; the first is the seeding of the double-pulse with two different wavelengths within the 200μs and the other is the double pass amplifier enables high energy. The power oscillator is a three meter long ring resonator. The length is dictated by the narrow spectral line width requirement; the ring configuration is to achieve a single transverse mode operation. The side pump volume and the TEM_{00} mode are closely matched to 2.3mm diameter.

The crystal is pumped with 3.2 joules of 792nm pump radiation to produce 90mJ of single Q-switched output and 130mJ of double pulsed output. The amplifier rod is twice the size of the oscillator and the pump energy is thus doubled.

The output of both pulses for the oscillator and amplifier are shown in Figure 1 and 2.

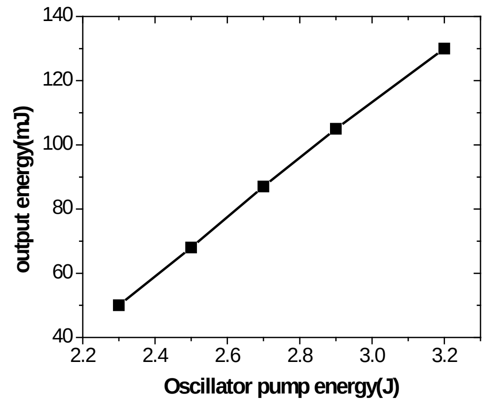

Figure 1. Oscillator performance

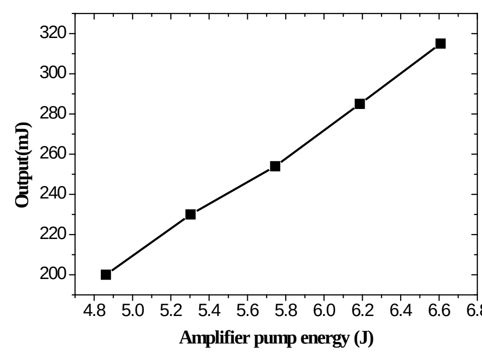

Figure 2. Amplifier performance

The operating principle of Ho:Tm lasers is well understood[9-12] and will only be briefly described here. In Ho:Tm:YLF the Tm ions are excited with 792 nm radiation from $^3H_6$ to $^3H_4$. A 6% Tm concentration is selected to secure self-quenching that warrants a quantum efficiency of close to 2. Thus for every photon absorbed in the Tm $^3H_4$, two atoms are produced in the Tm $^3F_4$ manifold. Tm $^3H_6$ is promoted to the Tm $^3F_4$ via non-radiative energy transfer. Ideally, this results in 2 excitations in the Tm $^3F_4$ for every pump excitation in the Tm $^3H_4$. The actual quantum efficiency of this process is dependent on the Tm concentration and should approach 2 at high Tm concentrations. Lower Tm concentrations can promote other transitions which have a deleterious effect; higher Tm concentration raises the threshold without any added benefit. Energy is then transferred from $^3F_4$ to Ho $^5I_7$ and the 2 micron laser action occurs between the Ho $^5I_7$ and $^5I_8$. Since the thulium is not directly involved in the

actual 2 μm emission, the energy in the $^3F_4$ serves as a reservoir to repopulate the holmium.

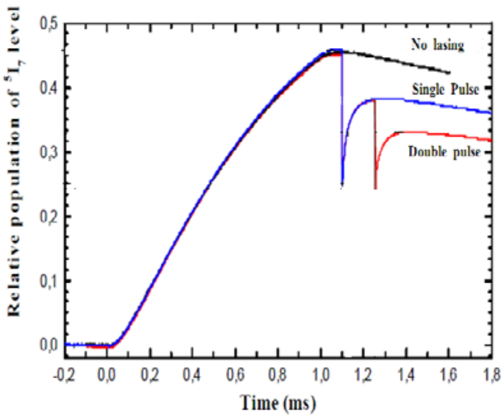

Figure 3. The relative population of the Ho upper laser level in three distinct conditions for 1ms pumps.

For DIAL application, most other systems use either two complete lasers or are forced to pump twice to produce two pulses within hundreds of microseconds. Ho:Tm:YLF operates much more efficiently in double pulse format than single pulse. Due to the long upper laser level life time and the energy stored in the Tm ion, the Holmium gets repopulated after the first Q-switch pulse. The second pulse is then extracted by simply opening the Q-switch. It has been shown that the energy ratio of the two pulses can be adjusted by controlling the first Q-switch time with respect pump pulse. Figure 3 represents the mechanism behind this phenomenon. The top trace represents a no lasing condition in which population continues to grow until a little after end of the pump pulse, typically 100μs and decays in 10 to 15ms. In single pulse operation, as soon as the Q-switch is fired and the population is depleted down to threshold, the Ho $^5I_7$ population then increases due to the rapid reduction the Ho $^5I_7$ population while the Tm $^3F_4$ population is intact. As a result, the Tm $^3F_4$ and Ho $^5I_7$ manifolds are no longer in quasi-thermal equilibrium. Thus the excited Tm ions in the $^3F_4$ manifold transfer the energy and repopulate the Ho ions until the Tm $^3F_4$ and Ho $^5I_7$ manifolds reach a quasi-thermal equilibrium again. This process takes about 150μs and results in the recovery of 50% of the depleted population at that moment the Q-switch can be fired again to extract additional energy.

Seeding is achieved by a variation of a ramp-and-fire scheme called push-and-pull method, in which the ‘on’ and ‘off’ line pulses are fired as the resonator mirror is pushed and pulled, respectively. The seed laser is injected through the 75% reflective output coupler. Close to the laser gain peak, the length of the resonator is adjusted by pushing one of the resonator mirrors to produce a resonance signal at which time the ‘on’ line pulse is fired.

This wavelength dwells in the system to be used as local oscillator for the lidar return. The length of this time is governed by the desired measurement range. If a 7.5km measurement is desired, the seed laser will be kept on for 50 microseconds before it is replaced by the ‘off’ line. Then the piezo-electric actuator pulls the length of the resonator to its original position, providing another resonance peak for the ‘off’ line pulse.

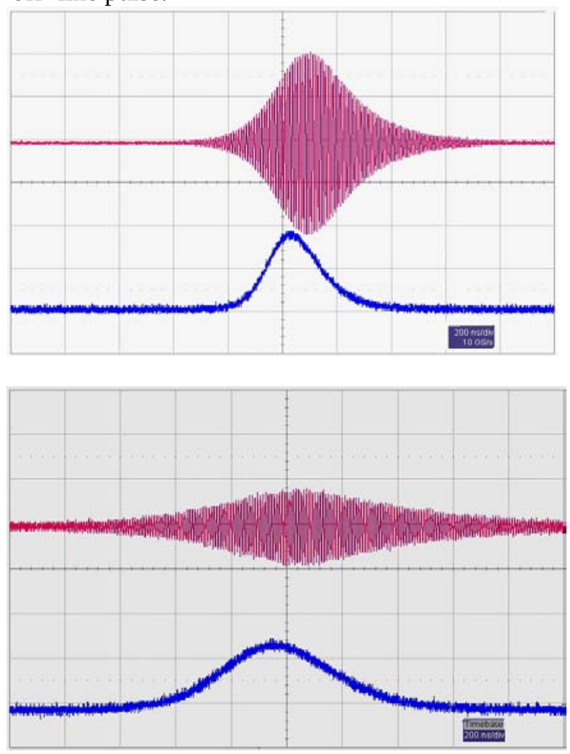

Figure 4a and b show the heterodyne signal of the local oscillator with the corresponding temporal pulse.

The system has an inbuilt heterodyne monitoring system derived from the seed laser that is split using a 105MHz acousto-optic modulator. The 0th order beam is used for generation of a local oscillator, which is routed via fiber optics to a monitor detector and a dual balanced return signal detector. The first order beam from the modulator is routed to seed the laser, thus providing an offset to the pulsed laser. Any scatter in the system is mixed to produce the diagnostic monitor signal. From which many aspects of the laser spectral characteristics can be determined. The measurements of the line width of each pulse shows both pulses produce near Fourier transform limit line width. The second pulse has a slightly narrow line width corresponding to its longer pulse length. A frequency jitter of +/- 1.5 MHz is measured on each of the pulses using heterodyne

method. The fast Fourier transform of this signal is measured and analyzed to look at frequency jitter over time. This same signal also provides the line width information at the FFT half power point. In addition, frequency chirp information can be extracted by splicing the heterodyne data and looking at the frequency at different places in the signal.

3. Conclusion

We have designed a Coherent DIAL instrument with high energy at 2-μm and is ready to be fielded. This instrument is an important addition to the myriad of other instruments that are developed to measure the CO_2 concentration to the very high degree of accuracy required by the science objective.

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